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Solar and Net Radiation at Bushland, Texas, 1968–77

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Solar and Net Radiation at Bushland, Texas, 1968–77

By W. C. Johnson and R. G. Davis[1]

ABSTRACT

At Bushland, Tex., continuous measurements of solar radiation and net radiation over a shortgrass ground cover were made for 10 years. Average annual totals were: positive net radiation, 85,736 cal/cm^2; negative net radiation, 24,951 cal/cm^2; and solar radiation, 160,246 cal/cm^2. The total annual solar energy was sufficient to evaporate an 8.9-foot depth of water. At solar noon on a clear day near the summer solstice, the flux of incoming solar radiation reached a peak rate of 1.48 cal/cm^{2}min (1.04 hp/yd^2). Average solar radiation on a clear day, expressed as a fraction of solar radiation at the outer limits of the atmosphere, varied from about 72% in September to 78% during February through May because of differences in atmospheric transmittance. The average negative (nighttime, outgoing) net radiation, expressed as a fraction of average positive (daytime, incoming) net radiation, ranged from 16% in July to 75% in December. The average radiation balance was positive in all months because the ground in this area is seldom snow covered. Positive net radiation over shortgrass averaged 57.5% of solar radiation during the growing season (April through September). Positive net radiation over an irrigated crop at Bushland is typically about 65% of solar radiation. Positive net radiation averaged only 44% of solar radiation during the winter (December through February) because of the low sun angle and occasional snow and because vegetation and soil reflect radiation better at this time of year. During the summer (June through August) the frequency distribution of daily solar radiation amounts is highly negatively skewed; near the summer solstice, the average amount of solar radiation is exceeded about 65% of the time. Index terms: atmospheric transmittance, atmospheric turbidity, radiation balance, soil heat flow, solar energy.

INTRODUCTION

Fuel shortages, pollution hazards, and rising costs emphasize the fact that we cannot continue to live indefinitely on "capital" energy sources (fossil fuels and atomic energy), but must learn to live on "income" energy (Brinkworth 1972). Solar energy is an attractive energy source because it is replenishable and environmentally benign. Except for agriculture, not much use has been made of it. But solar energy is diffuse and variable, collection areas must be large, and the energy must be stored. Technological problems in these areas must be solved before solar energy can be utilized on a large scale.

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Estimates of solar energy's potential for supplying the world's energy needs range from only small-scale home uses (such as for water and space heating) to as much as 80 percent of all energy needs (Brinkworth 1972, Commoner 1976). There is a growing need for quantitative information about solar radiation. This information is needed not only by scientists, farmers, and ranchers (as in the past), but increasingly by architects and engineers.

Solar- and net-radiation measurements are used in agriculture to estimate evapotranspiration by plants and evaporation from reservoirs, and to predict phenological events or the duration of plant growth stages (U.S. Geological Survey 1954, Tanner 1960, Tanner and Lemon 1962, Fritschen 1965, 1967). Solar radiation characterizes the local potential of the sun as a source of power better than net radiation because it is a measure of the total incoming shortwave radiant energy. Net radiation is the better indicator of the energy available at the earth's surface for evaporating water and warming the soil and air.

The U.S. Weather Bureau began making solar radiation observations more than 60 years ago (Hand 1949). Early data were used to develop estimating equations of solar radiation for places where actual observations were not available (Fritz 1949, Fritz and McDonald 1949). Local summaries of solar radiation have been published at a number of locations in the United States (Hand 1949, McQuigg and Decker 1958, McWhorter and Brooks 1965, Branton et al. 1972), and a report was published in 1975, summarizing solar radiation at 20 locations in the North Central States (Baker and Klink 1975). But continuous observations of net radiation are still scarce and have probably been made yearlong at fewer than a dozen places in North America.

This report presents the results of a 10-year project of continuously recording solar and net radiation at the USDA Southwestern Great Plains Research Center, Bushland, Tex. (12 mi west of Amarillo, lat. 35°10′ N., long. 102°5′ W.).

DEFINITIONS AND UNITS OF MEASURE

Solar radiation, which the World Meteorological Organization (WMO) terms "global solar radiation received on a horizontal surface" (World Meteorological Organization 1965), includes radiation received directly from the sun, plus that which has been scattered or diffusely reflected by clouds or atmospheric turbidity. Its wavelength range is from 300 to 4,000 nm. About half of the energy of solar radiation reaching the earth's outer atmosphere is in the visible range (350 to 700 nm). Solar radiation is also called shortwave radiation.

Net radiation is defined by the WMO as the net flux (flow) through a horizontal surface (downward and upward) of total solar, terrestrial-surface, and atmospheric radiation. Terrestrial-surface and atmospheric radiation (also called longwave radiation) have wavelengths over 4,000 nm and are not visible. By convention, net radiation downward (toward the earth) is given a positive sign and net radiation upward (away from the earth) is given a negative sign. Negative net radiation occurs mostly at night and positive net radiation always in the daytime.

Outer limits radiation is the daily amount of solar radiation flux through a horizontal surface at the top of the atmosphere, usually expressed in calories per square centimeter per day (cal/cm^{2}day). Its numerical value varies with location and time of year and can be found in handbook tables (List 1951).[2]

Radiant energy per unit of surface area is expressed as gram calories per square centimeter (cal/cm^2). The gram calorie (or small calorie) is the energy required to raise the temperature of 1 g of water 1° C.[3]

Flux density is the rate of flow of energy per unit of horizontal surface area. It is expressed as calories per square centimeter per unit of time (cal/cm^{2}day, for example).

INSTRUMENTATION AND DATA COLLECTION

Each of the radiation-measuring instruments used in this study depends on a thermopile for its operation. The type of thermopile used in radiation instruments consists of multiple ther-

[2]These tabular values were calculated assuming a solar constant of 1.94 cal/cm^{2}min. The value currently used is 2.00 cal/cm^{2}min.

[3]This unit should not be confused with the more commonly encountered kilogram calorie used to measure the energy content of foods, a unit 1,000 times larger.

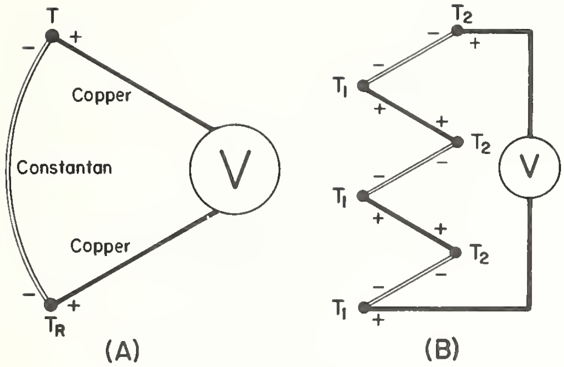

FIGURE 1.—Thermopiles. (A) Two copper-constantan thermocouples arranged to measure temperature, T; T_R is the reference temperature, and V is a voltmeter which indicates an emf proportional to T-T_R. (B) A six-junction thermopile as might be used to measure the difference between temperatures T_1 and T_2

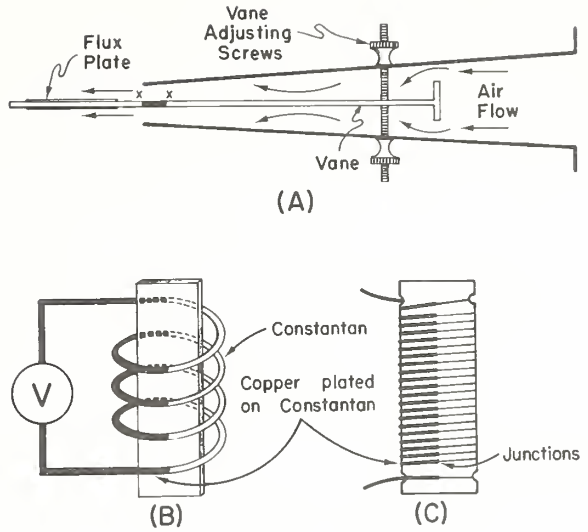

FIGURE 2.—Net radiometer. (A) Cross-section of nozzle, showing the adjustable vane for equalizing air flow over the top and bottom of the flux plate. (B) A thermopile is formed by winding the flux plate with constantan wire and plating one-half of the turns with copper. (C) Actual appearance of a net radiometer flux plate (the typical number of junctions is 200).

mocouples in series. A thermocouple is a junction of two unlike metals (one commonly used combination of metals is copper and the alloy, constantan) that produces a voltage proportional to its temperature. Thermocouples are often used to measure temperature, as in the case of the two-junction thermopile (fig. 1A), one junction of which is at a known reference temperature, T_R, and the second junction is at the temperature to be measured, T.

In more complex thermopiles (fig. 1B) alternate junctions are at one of two temperatures, T_1 and T_2, whose difference is to be measured. Thermopiles used in instruments for measuring net and solar radiation may have from 10 to several hundred junctions. Voltages generated by successive junctions in the series (junction pairs) are in opposition and the output of the thermopile is the net voltage generated by a junction pair multiplied by the number of junction pairs. A voltage-measuring device, V (which in our apparatus was a millivolt recorder), indicates the output of the thermopile.

To measure net radiation, we used, at different times, one of two brands of ventilated net radiometers, also called net pyrradiometers (World Meteorological Organization 1965). The net radiometer consists of a horizontal heat-flux plate, blackened on both sides to absorb all wavelengths of radiation. Strong air currents are directed symmetrically along the upper and lower surface of the plate (fig. 2A) so that the "ventilation functions" of the two surfaces are alike and the effect of the ambient wind is minimized.[4] If this condition is met, the temperature difference between the top and bottom of the flux plate, and the voltage output of its thermopile, will be proportional to net radiation.

The thermopiles of the two types of net radiometer we used were constructed by winding the plate with fine constantan wire and then plating one-half of the windings with copper (fig. 2B, 2C). Since copper's electrical conductivity is greater than that of constantan, the plated sections function as if made entirely of copper (Wilson and Epps 1920).

During the first 2 years of the study, we used a commercial net radiometer of the Gier and Dunkle (1951) type (fig. 3). Because of its low ventilation rate and lack of adjustment for symmetrical ventilation of the top and bottom of the flux plate, we later replaced it with a modified Agmet instrument of the type described by Suomi et al. (1954).[5]

Modifications of the Agmet net radiometer

[4] For net radiometer theory, see Suomi et al. (1954).

[5] Obtained in 1958 from Agmet Products Co., Middleton Wis.

consisted of changes in the blower (fig. 4) and flux plate (fig. 5). A remote blower powered by a 1/3-hp, 3,450-rpm, split-phase electric motor[6] was substituted for the original blower, which was attached directly to the nozzle and powered by a smaller, rather short-lived, 1/25-hp, 5,000-rpm motor. A more rugged flux plate was substituted for the original (which was wound on a glass plate and supported by printed-circuit-type connecters secured to the glass by an adhesive). The replacement was wound on a laminated fiberglass-plastic plate and held in place by soldering terminals riveted to its corners. The plate was wound with 200 turns 0.005 inch-diameter constantan wire, one-half of which were plated with copper (see fig. 2B). A heater winding of 36-gage enameled copper wire was wound between the turns of constantan wire for use in vane adjustment (Suomi et al. 1954). Finally, the flux plate was painted with black epoxy paint followed by a coat of black optical lacquer. The modified Agmet radiometer and remote blower operated continuously for 8 years without an appreciable change in calibration.

[6]The electric motor and special blower were obtained from Phelps Fan Manufacturing Co., Little Rock, Ark.

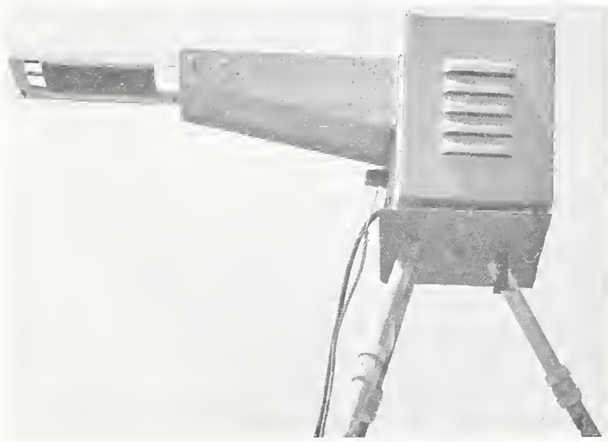

FIGURE 3.—Commercial Gier and Dunkle type of ventilated net radiometer.

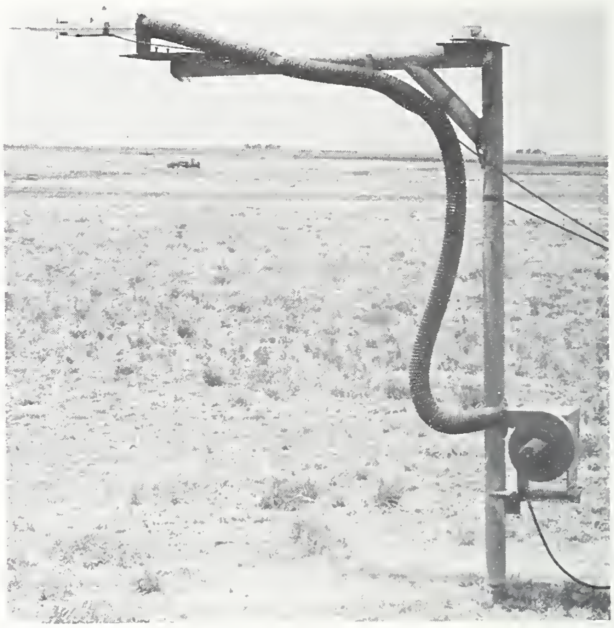

FIGURE 4.—Modified Agmet radiometer showing remote blower.

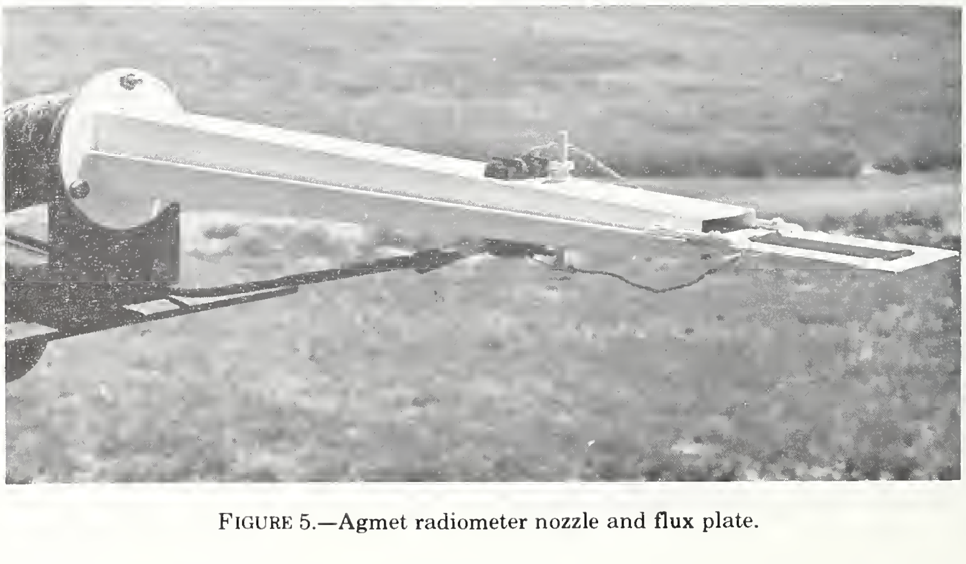

FIGURE 5.—Agmet radiometer nozzle and flux plate.

A similarly constructed heat flow plate was buried in the soil at a ¾-inch (1.9-cm) depth to measure soil heat flow.

The net radiometer was calibrated at approximately 3-month intervals by comparison with an Eppley pyranometer (using the shading method) at solar noon (Suomi et al. 1954). The vane of the Agmet-type radiometer was adjusted once or twice annually by connecting a source of 6-V d.c. to the heater winding, operating the radiometer in total darkness, and adjusting the vane so that the output of the thermopile was zero. Vane adjustment was also checked occasionally by verifying that the calibration constant of the radiometer was the same when inverted as when in the normal position.

Solar radiation was measured using an Eppley pyranometer (sometimes called a pyrheliometer), which is the most widely used solar radiation instrument in North America and has been adopted as a standard for comparison in both the United States and Canada (Drummond 1966). It consists of a thermopile incorporated in a round, horizontal sensing disk hermetically sealed in a glass globe containing dry air (McDonald 1951). There is a pattern on the surface of the disk formed by thin silver strips coated with black or white pigment. Two different models were used; the first was a Weather Bureau type (fig. 6) in which the black and white strips form concentric rings. The second (used from June 1972 through December 1977) was a temperature-compensated model 8-48A (fig. 7), in which the contrasting strips are sectors of a circle. In both instruments, alternate junctions of the thermopile are in thermal but not electrical contact with either a black or a white area. The black and white areas respond similarly to longwave (thermal) radiation, such as that received from the glass globe, and their relative temperature is not affected. When exposed to solar radiation, however, the black and white strips are heated differentially and the thermopile produces an output voltage proportional to the flux rate of solar radiation.

The black optical lacquer pigment of the Weather Bureau type Eppley pyrheliometers first used in this project faded in time, causing a gradual decrease in the output voltage of as much as 12%. To insure the accuracy of our data, we kept track of the instruments' calibration constants by comparing them with a pyranometer whose calibration constant was accurately known and which was not exposed to light except when used for calibration purposes. Our Weather Bureau type pyranometers had been exposed to about 24 months of summer sunshine before being used in this project and had decreased in output from the factory calibration by 9% and 6%. But the calibration of both instruments had become stabilized and did not change appreciably during this study.[7] The

FIGURE 6.—Weather Bureau type of Eppley pyranometer.

[7]Robinson (1966) reported that the output of these pyranometers stabilizes after about 30 months use.

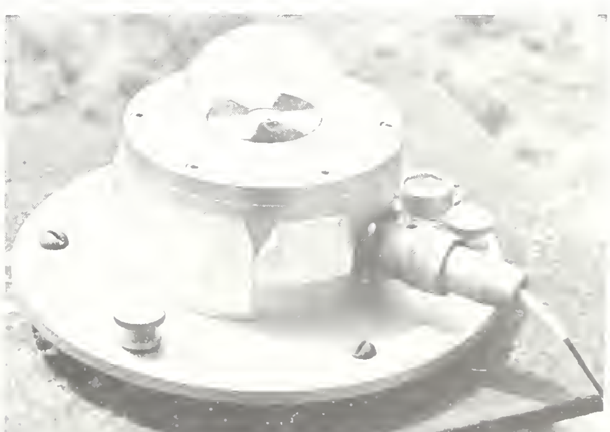

FIGURE 7.—Temperature-compensated Eppley pyranometer, model 8-48A.

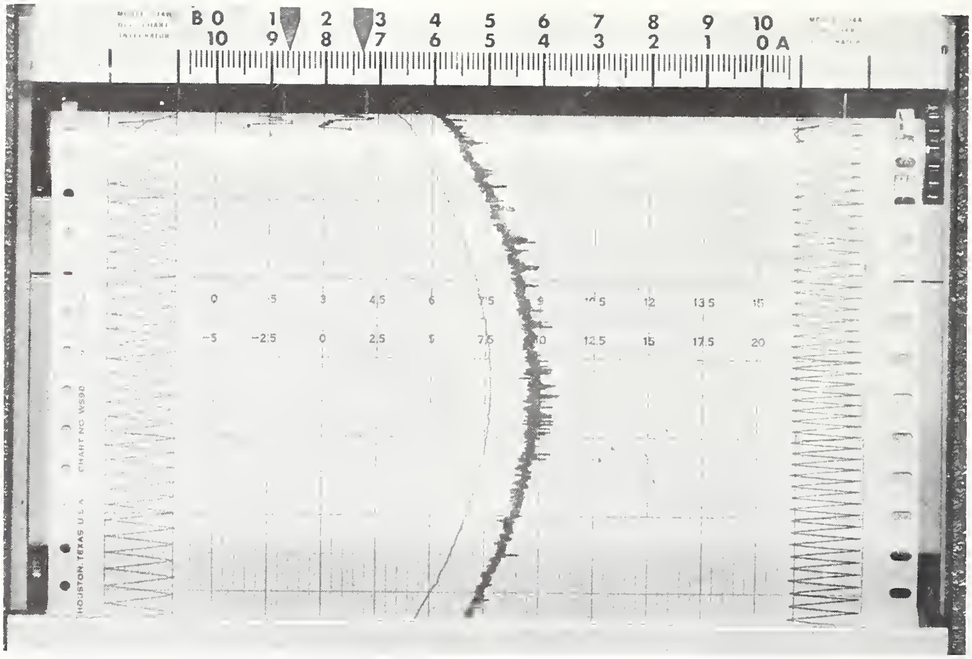

FIGURE 8.—Millivolt recorder for net and solar radiometers. Integrator traces are along chart margin.

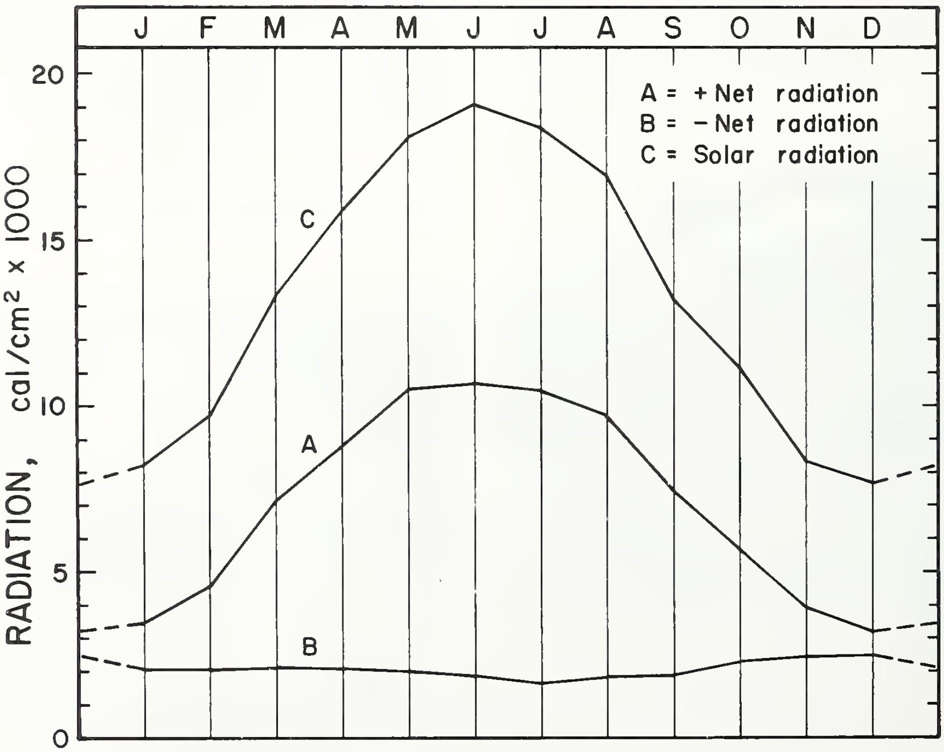

FIGURE 9.—Average monthly (A) positive net radiation, (B) negative net radiation, and (C) solar radiation.

black pigment on the temperature-compensated pyranometer used in the final 5½ years of observation was apparently superior; its calibration constant did not change while in use.

The outputs of the pyranometer and net radiometer were recorded on a two-channel millivolt recorder (fig. 8) equipped with chart integrators.[8] Daily totals of solar and net radiation (proportional to the areas under the curves) were taken from the integrator records (the zigzag traces on the chart margins).

DATA AND DISCUSSION

Radiation Sums and Averages

Monthly sums, annual sums, and 10-year averages of positive net radiation (+NR), negative net radiation (-NR), and solar radiation (SR) measured from 1968 through 1977 are given in table 1. The average total annual SR was 160, 246 cal/cm^2, which is enough energy to evaporate an 8.9-foot depth of water.[9] At a homeowner's electrical rate of \$0.06/kilowatthour (kWh), this amount of energy per acre would cost about \$450,000/acre per year.[10]

On an annual basis, total SR averaged 60% of outer limits radiation. On clear days, average SR ranged from about 72% of outer limits radiation in September to 78% from February through May.

Average monthly amounts of SR, +NR, and -NR are shown in figure 9. In December, -NR averaged about 75% of the +NR but in July, it was only about 16%. Although the ratio of -NR in December to that in July is nearly the same as the ratio of the number of nighttime hours in the 2 months (1.5 to 1) (fig. 10), more than day length determines the amount of -NR; it is also affected by the radiative temperature and emissivity of the ground surface, the air temperature and temperature gradient, wind speed, and the amount of water vapor and carbon dioxide in the air (Gates 1962, Brooks et al. 1963, Linacre 1963, Swinbank 1963, Humphreys 1964, Businger 1965, Baker 1966, Polovarapu 1970).

Net radiation calculated on a whole-day basis is called "radiation balance," which is defined as global SR minus reflected SR minus net longwave cooling. Numerically, this is the same as the algebraic sum of the +NR and -NR. Some maps of radiation balance have been published for different parts of the world but these were based on calculations rather than observed values (Budyko 1968, Hare and Hay 1974).

The radiation balance at Bushland is positive for all months (table 1, fig. 9), which is not true for higher latitudes. At Palmer, Alaska, in the Matanuska Valley (lat. 61°36′ N.) the average daily radiation balance is negative from mid-October to mid-March (Branton et al. 1972). Radiation balance at Palmer decreases rapidly in the fall until mid-November and then (with continuous snow cover) remains negative, changing little until late January. Radiation balance at Palmer reaches a maximum of about +250 cal/cm^2 day in mid-June and a minimum of -73 cal/cm^{2}day around December 22. At Bushland, the average maximum radiation balance is +295 cal/cm^{2}day in June and the minimum is about +25 cal/cm^{2}day in December.

The duration of the period of negative radiation balance at northern latitudes corresponds to the period of snow cover. Radiation balance is negative from November through February over all of Canada (Hare and Hay 1974) and at St. Paul, Minn. (Blad and Baker 1971). Snow affects the radiation balance much less at Bushland than it does at these locations because Bushland gets only 13 inches of snow annually, the soil seldom freezes deeper than about 4 inches, and the ground remains covered with snow only a few days at a time. For the months May through August, the radiation balance at St. Paul remains constant at about 50% of SR (Blad and Baker 1971) compared to 47% at Bushland and 53% at Palmer.

Table 2 shows average daily SR for each standard Climatological Week of each year during the 10-year period and the average of weekly averages. Table 3 gives similar information on +NR.

(*Continued on page 13.*)

[8]The recorder was a Servo/Riter II, model FLO2W6D from Texas Instruments Inc., Houston, Tex.; the chart integrator was a model 234AB from Disc Instruments Inc., Costa Mesa, Calif.

[9]At 70° F (21° C) it takes about 1,500 cal of energy to evaporate 1 inch (2.5 cm) depth of water 1 cm^2 in cross section.

[10]1 kWh=860,000 cal.

Table 1.—Monthly and annual sums and averages of positive and negative net radiation and solar radiation, 1968-77

[Calories per square centimeter]

Period	Measurement[1]	Year 1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	Sum	Average	Daily average
Jan.	+NR	3,350	4,049	3,056	3,256	3,902	2,793	3,477	3,337	3,649	3,732	34,601	3,460	111.6
	-NR	2,225	2,160	2,189	2,389	2,397	1,779	1,576	2,641	2,927	2,627	22,910	2,291	73.9
	SR	8,070	8,178	8,753	8,544	8,674	7,279	7,589	8,091	8,837	8,247	82,262	8,226	265.4
Feb.	+NR	4,634	4,717	4,828	4,237	5,255	4,603	5,173	3,105	4,381	4,768	45,701	4,570	161.5
	-NR	1,845	2,026	1,954	1,893	2,193	1,758	2,147	1,924	2,476	2,208	20,424	2,042	72.2
	SR	9,877	9,098	9,994	10,232	10,725	8,681	10,722	7,744	9,642	10,203	96,918	9,692	342.5
Mar.	+NR	6,633	7,889	6,077	7,721	7,897	7,007	7,315	7,271	6,958	7,227	71,995	7,200	232.2
	-NR	1,705	1,999	2,020	2,282	2,348	1,880	2,010	2,110	2,504	2,476	21,334	2,133	68.8
	SR	12,310	13,442	12,116	14,920	14,421	11,382	13,391	13,455	13,997	13,640	133,074	13,307	429.3
April ...	+NR	7,840	9,376	9,899	8,999	9,828	8,418	8,799	8,858	8,141	7,661	87,819	8,782	292.7
	-NR	2,287	2,160	2,523	2,129	2,235	1,808	2,025	2,281	2,093	1,613	21,154	2,115	70.5
	SR	16,625	15,695	17,387	16,517	16,943	14,582	16,925	15,414	14,849	13,818	158,755	15,876	529.2
May	+NR	9,260	11,352	12,171	10,264	10,242	10,477	10,681	11,040	10,412	9,356	105,255	10,526	339.5
	-NR	2,129	2,050	2,161	2,155	1,866	1,886	2,133	2,067	1,984	1,699	20,130	2,013	64.9
	SR	17,177	15,505	20,971	19,128	16,695	18,403	19,782	19,013	17,733	16,668	181,075	18,108	584.1
June	+NR	10,832	10,943	11,422	11,071	11,048	11,464	10,362	10,477	10,511	9,142	107,272	10,727	357.6
	-NR	2,466	2,200	1,779	1,764	1,716	1,766	1,749	1,953	1,818	1,509	18,720	1,872	62.4
	SR	19,914	18,216	19,151	19,280	19,180	20,547	19,144	18,048	19,349	18,389	191,218	19,122	637.4
July	+NR	10,372	11,723	10,689	10,036	11,741	10,027	10,142	9,903	10,359	10,224	105,216	10,522	339.4
	-NR	2,160	1,550	1,361	1,687	1,528	1,484	1,838	1,855	1,681	1,465	16,609	1,661	53.6
	SR	18,500	19,043	18,510	17,919	18,353	17,861	19,624	17,093	18,415	19,281	184,599	18,460	595.5
Aug. ...	+NR	9,414	9,680	10,085	10,352	9,324	10,484	9,521	9,628	9,467	9,521	97,476	9,748	314.4
	-NR	2,040	1,690	1,954	1,731	1,658	1,905	1,892	2,295	1,964	1,173	18,302	1,830	59.0
	SR	16,680	17,111	17,405	16,520	16,286	18,675	16,023	18,131	17,621	15,483	169,935	16,994	548.2
Sept. ...	+NR	8,775	7,923	7,300	7,453	7,402	7,075	6,588	6,793	7,488	7,365	74,162	7,416	247.2
	-NR	2,533	1,790	1,845	1,922	1,774	1,684	1,772	2,358	1,825	1,363	18,866	1,887	62.9
	SR	14,733	12,402	13,084	13,130	13,343	13,090	12,119	13,561	12,912	13,801	132,175	13,218	440.6
Oct.	+NR	6,462	5,667	5,799	6,226	4,819	5,934	5,444	5,913	5,672	4,873	56,809	5,681	183.3
	-NR	2,380	1,814	2,107	2,131	1,836	2,299	2,546	2,834	2,304	2,161	22,412	2,241	72.3
	SR	12,512	9,741	11,032	11,540	10,140	11,984	10,116	13,587	10,391	10,994	112,037	11,204	361.4

Nov. ...	+NR	3,482	4,533	4,216	4,377	3,062	3,612	4,279	3,801	3,980	3,307	38,749	3,875	129.2
	-NR	2,159	2,672	2,457	2,248	2,221	2,198	2,729	2,653	2,549	2,303	24,189	2,419	80.6
	SR	7,100	9,429	8,635	8,211	7,768	8,414	8,390	8,971	8,638	8,254	83,810	8,381	279.4
Dec.	+NR	3,656	2,993	3,357	3,004	3,148	3,475	3,193	3,011	3,762	2,707	32,306	3,231	104.2
	-NR	1,988	2,288	2,632	2,176	2,383	2,011	2,860	2,741	3,043	2,334	24,456	2,446	78.9
	SR	8,074	7,098	8,054	6,880	7,168	8,144	7,320	8,167	8,370	7,322	76,597	7,660	247.1
Annual .	+NR	84,812	90,845	88,899	86,996	87,668	85,369	84,974	83,137	84,780	79,883	857,363	85,736	234.7
	-NR	25,917	24,399	24,982	24,507	24,155	22,458	25,277	27,712	27,168	22,931	249,506	24,951	68.3
	SR	161,572	154,958	165,092	162,821	159,696	159,042	161,145	161,275	160,754	156,100	1,602,455	160,246	438.7

[1]+NR, positive net radiation; -NR, negative net radiation; SR, solar radiation.

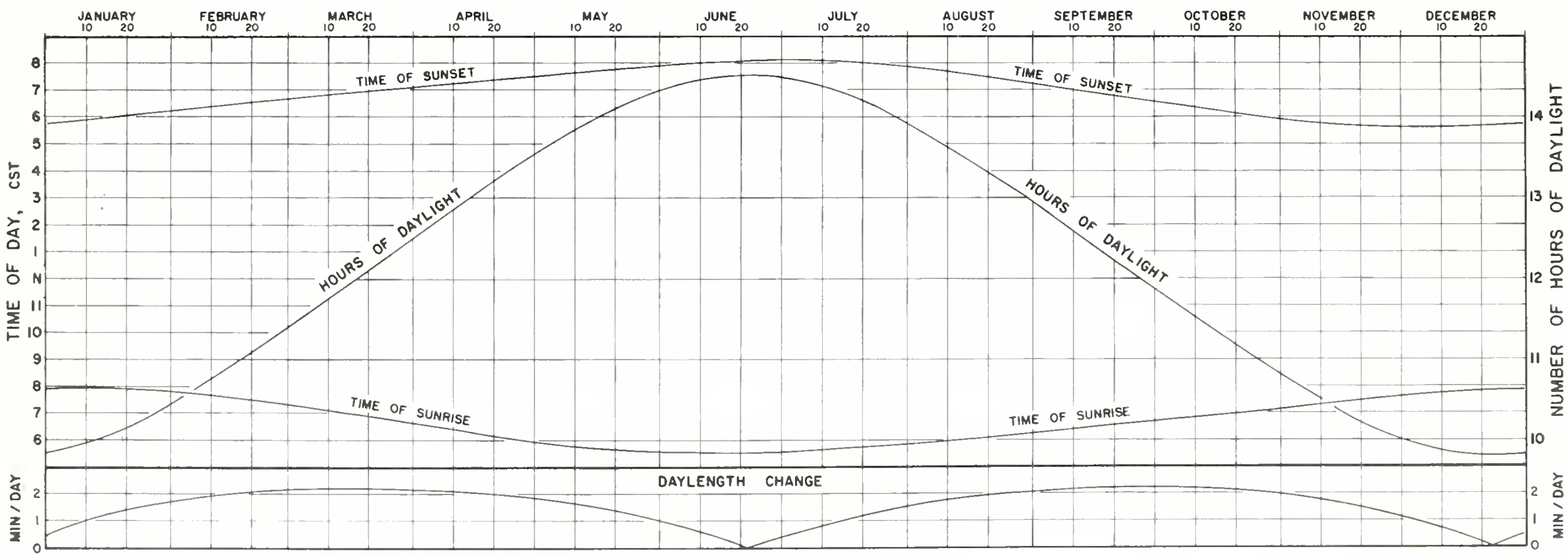

FIGURE 10.—Times of sunrise and sunset, number of daylight hours, and daily change in day length at Bushland, Tex., 1978.

Table 2.—Average daily solar radiation by Climatological Week, 1968-77, and 10-year average

[Calories per square centimeter per day]

Week	Period	Year 1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	10-yr average[1]
1	Mar. 1-7	304	347	333	464	443	466	411	426	337	398	387
2	Mar. 8-14	359	416	395	487	482	304	357	286	419	429	393
3	Mar. 15-21	339	466	413	495	492	464	398	469	501	477	451
4	Mar. 22-28	471	486	509	456	471	315	500	507	498	427	464
5	Mar. 29-Apr. 4 ...	473	449	332	530	476	328	542	567	564	533	479
6	Apr. 5-11	527	515	575	572	517	508	590	397	533	512	525
7	Apr. 12-18	502	431	498	517	577	537	648	485	470	313	498
8	Apr. 19-25	608	584	682	514	569	497	599	543	570	468	563
9	Apr. 26-May 2	582	645	653	641	628	534	408	636	421	526	567
10	May 3-9	501	450	697	619	476	621	676	667	496	549	575
11	May 10-16	537	575	726	638	466	497	688	588	631	457	580
12	May 17-23	536	543	671	629	620	636	657	645	610	588	614
13	May 24-30	566	660	642	556	553	621	579	529	532	537	578
14	May 31-June 6	590	630	568	627	692	644	565	638	604	637	620
15	June 7-13	607	556	686	532	587	650	652	570	621	641	610
16	June 14-20	658	478	657	686	637	738	693	603	715	670	654
17	June 21-27	716	740	692	723	700	688	655	591	662	544	671
18	June 28-July 4	566	706	627	676	484	660	608	548	573	586	603
19	July 5-11	544	558	651	652	575	598	637	577	629	620	604
20	July 12-18	631	607	667	677	647	499	645	602	506	657	614
21	July 19-25	655	579	396	444	590	627	666	543	637	611	575
22	July 26-Aug. 1	642	659	571	487	636	526	573	505	614	586	580
23	Aug. 2-8	651	631	641	526	544	633	491	624	580	629	595
24	Aug. 9-15	508	643	563	492	546	609	603	561	618	437	558
25	Aug. 16-22	561	575	483	532	535	630	536	614	579	481	553
26	Aug. 23-29	457	410	617	567	451	594	392	575	532	430	503
27	Aug. 30-Sept. 5 ...	565	395	517	553	351	527	528	490	484	478	489
28	Sept. 6-12	578	292	530	540	503	388	531	463	426	496	475
29	Sept. 13-19	548	438	319	363	448	391	279	431	442	472	413
30	Sept. 20-26	481	454	404	334	499	477	272	447	391	418	418
31	Sept. 27-Oct. 3	486	479	410	446	481	416	509	478	379	456	454
32	Oct. 4-10	432	435	426	436	417	317	331	488	376	303	396
33	Oct. 11-17	383	308	229	382	378	415	298	439	391	429	365
34	Oct. 18-24	408	241	384	326	211	423	326	411	314	325	337
35	Oct. 25-31	391	211	342	302	227	388	277	387	239	320	308
36	Nov. 1-7	229	312	305	338	364	304	275	309	328	272	304
37	Nov. 8-14	241	329	258	326	247	254	275	359	256	336	288
38	Nov. 15-21	246	323	323	252	162	297	295	272	282	296	275
39	Nov. 22-28	239	294	273	219	265	256	280	271	279	248	262
40	Nov. 29-Dec. 5	292	222	262	160	223	280	269	288	294	228	252

See footnote at end of table.

Table 2.—Average daily solar radiation by Climatological Week, 1968-77, and 10-year average—*Continued*

[Calories per square centimeter per day]

Week	Period	Year										10-yr average[1]
		1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	
41	Dec. 6-12	274	189	286	247	181	289	248	276	232	275	250
42	Dec. 13-19	275	263	239	229	242	269	246	296	280	244	258
43	Dec. 20-26	230	260	257	253	277	266	218	192	281	218	245
44	Dec. 27-Jan. 2	251	254	266	178	244	181	199	256	263	212	230
45	Jan. 3-9	259	242	310	267	283	152	197	267	273	215	247
46	Jan. 10-16	300	240	237	258	256	289	219	284	282	286	265
47	Jan. 17-23	163	237	234	262	310	287	249	278	282	266	257
48	Jan. 24-30	265	310	310	338	283	274	307	247	310	293	294
49	Jan. 31-Feb. 6	343	363	330	308	340	304	356	125	226	320	302
50	Feb. 7-13	291	349	387	367	346	251	388	338	316	326	336
51	Feb. 14-20	287	177	406	335	372	304	335	290	407	346	326
52	Feb. 21-28(29)	359	406	312	438	361	342	443	323	418	396	380

[1]The average of the 10 yearly averages.

Table 3.—Average daily positive net radiation by Climatological Week, 1968-77, and 10-year average

[Calories per square centimeter per day]

Week	Period	Year										10-yr average[1]
		1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	
1	Mar. 1-7	189	161	173	211	237	241	202	239	163	214	203
2	Mar. 8-14	189	221	187	254	254	189	216	164	213	214	210
3	Mar. 15-21	153	284	194	261	262	281	226	265	243	251	242
4	Mar. 22-28	302	329	247	254	273	193	273	267	250	231	262
5	Mar. 29-Apr. 4	243	286	213	279	270	222	285	305	279	295	268
6	Apr. 5-11	258	291	337	306	291	215	301	221	271	252	274
7	Apr. 12-18	248	274	292	301	321	348	333	289	251	171	283
8	Apr. 19-25	295	349	385	280	339	293	321	308	344	285	320
9	Apr. 26-May 2	287	373	355	340	369	331	222	348	253	303	328
10	May 3-9	266	314	393	340	286	356	368	367	300	289	328
11	May 10-16	329	375	408	329	298	282	370	359	370	269	339
12	May 17-23	297	340	396	330	373	360	334	383	341	342	350
13	May 24-30	303	431	390	312	355	346	345	312	320	296	341
14	May 31-June 6	330	383	328	335	392	386	333	354	353	240	343
15	June 7-13	330	344	423	319	325	372	361	335	355	320	438
16	June 14-20	377	335	380	401	393	406	363	354	372	326	371

See footnote at end of table.

Table 3.—Average daily positive net radiation by Climatological Week, 1968-77, and 10-year average—*Continued*

[Calories per square centimeter per day]

Week	Period	Year 1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	10-yr average[1]
17	June 21-27	385	406	424	413	384	361	345	346	346	320	373
18	June 28-July 4	284	399	376	390	316	354	315	316	294	334	338
19	July 5-11	309	372	361	359	377	320	368	345	349	337	350
20	July 12-18	399	333	375	354	394	277	327	352	315	344	347
21	July 19-25	361	374	242	259	397	376	316	307	369	311	331
22	July 26-Aug. 1	329	412	332	289	389	305	292	291	327	310	328
23	Aug. 2-8	329	366	354	322	291	383	293	351	340	347	338
24	Aug. 9-15	281	339	334	326	333	349	370	296	327	271	323
25	Aug. 16-22	327	300	298	355	289	358	304	334	287	315	317
26	Aug. 23-29	263	257	353	336	270	298	233	291	286	279	287
27	Aug. 30-Sept. 5	345	256	294	316	225	265	296	235	264	292	279
28	Sept. 6-12	315	194	285	276	312	219	286	229	235	279	263
29	Sept. 13-19	278	284	204	199	246	224	147	216	281	250	233
30	Sept. 20-26	265	290	218	209	241	250	152	230	224	205	228
31	Sept. 27-Oct. 3	247	279	215	272	232	214	277	232	215	215	240
32	Oct. 4-10	233	247	218	220	193	175	188	222	199	139	203
33	Oct. 11-17	197	191	127	192	168	219	163	188	218	184	185
34	Oct. 18-24	213	137	215	191	112	195	166	171	176	145	172
35	Oct. 25-31	182	122	169	173	115	164	147	162	126	138	150
36	Nov. 1-7	117	169	157	187	169	139	149	142	171	114	151
37	Nov. 8-14	128	180	127	148	115	109	156	143	110	126	134
38	Nov. 15-21	125	144	158	142	55	121	148	122	147	119	128
39	Nov. 22-28	108	117	126	125	73	111	126	116	122	90	111
40	Nov. 29-Dec. 5	130	94	109	38	100	97	115	107	120	82	99
41	Dec. 6-12	115	96	119	97	87	130	109	101	113	104	107
42	Dec. 13-19	110	130	102	118	99	121	109	97	121	85	109
43	Dec. 20-26	114	118	108	135	121	110	88	80	117	80	107
44	Dec. 27-Jan. 2	114	68	78	85	106	88	81	107	110	89	93
45	Jan. 3-9	111	117	16	40	104	24	78	103	109	96	80
46	Jan. 10-16	110	117	109	118	118	65	118	70	111	73	101
47	Jan. 17-23	68	130	131	121	137	141	122	140	112	148	125
48	Jan. 24-30	142	152	152	143	137	148	143	123	141	162	144
49	Jan. 31-Feb. 6	180	161	158	137	162	179	161	51	102	161	145
50	Feb. 7-13	128	162	182	149	161	125	174	181	146	156	156
51	Feb. 14-20	136	94	199	171	186	169	167	72	161	208	156
52	Feb. 21-28(29)	185	244	154	150	207	169	226	124	187	158	180

[1]The average of the 10 yearly averages.

Solar Radiation Frequency Distribution and Probabilities

Some investigators (Baker and Klink 1975) have questioned the value of daily SR averages as single-valued statistics because they are not symmetrically distributed about the mean. Especially in the warm season, the data are concentrated in the higher values and the frequency distribution tails off toward the lower, cloudy-day values. Graphs of the frequency distribution of daily SR values at Bushland and at Dodge City, Kans. (fig. 11) show highly negatively skewed daily SR in Climatological Week 17 (June 21–27). For such highly skewed data, the median is a more representative single-valued statistic than the average because (by definition) half of the values fall on either side of it (Brooks and Carruthers 1953, Baker and Klink 1975). Mean and median daily SR for Climatological Week 17 are, respectively, 656 and 701 cal/cm^{2}day at Dodge City and 643 and 679 cal/cm^{2}day at Bushland.

Observational data are more completely described if a statement of the dispersion of values about the central value (mean or median) is given in addition to the central value itself. Table 4 supplies this kind of information by listing amounts of daily SR that might occur each Climatological Week and the percent probability that they will be reached or exceeded. (Medians comprise the 50% column.) Observations for the preceding and following week were included with data for each Climatological Week so that the frequency distribution curve (which was plotted on log-normal probability paper and used for making probability statements) would be smoother. Median daily SR for week 17 at Bushland is 679 cal/cm^{2}day. The corresponding average daily SR from table 2 (10-year averages for weeks 16, 17, and 18 combined) is 643 cal/cm^{2}day. One would expect (from table 4) that during week 17 the average daily SR would be exceeded on about 65% of the days. In week 32, the median and average are 449 and 405 cal/cm^{2}day, respectively, and one would expect the average to be exceeded about 69% of the time. Comparable SR data (in the same format as table 4) are available for 20 Great Plains locations (Baker and Klink 1975) and for Palmer, Alaska (Branton et al. 1972).

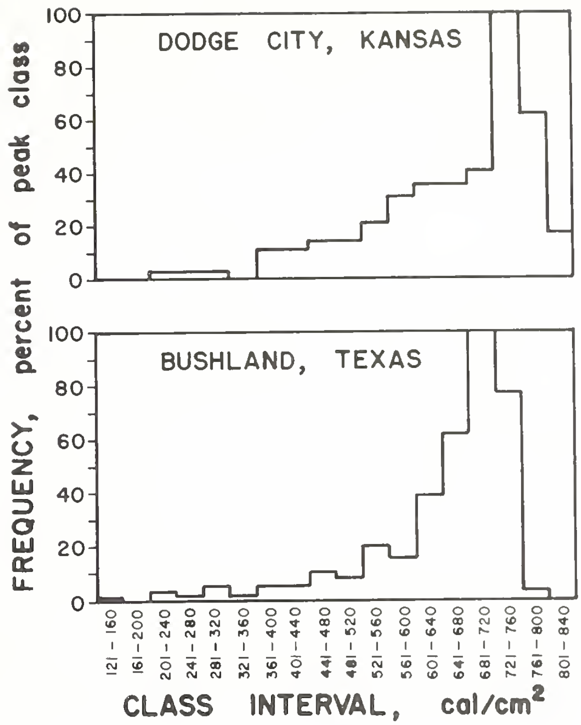

Figure 11.—Frequency distribution of daily solar radiation: (A) during Climatological Week 17 (June 21–27) at Dodge City, Kans., 1952–70; and (B) during Climatological Weeks 16–18 (June 14–July 4) at Bushland, Tex., 1968–77.

Seasonal Variations

The frequency distribution of both SR and atmospheric transmittance at the midpoint of each month are shown in figure 12.[11]

On any day in mid-April there is a 10% chance that SR will be at least 76% of the outer limits radiation, and a 90% chance that SR will be at least 30% of the outer limits radiation. As would be expected, the range in atmospheric transmittance is less during the warm-season months because frequent cumulus clouds make absolutely clear days unlikely, but there is also little chance of the completely overcast days that accompany large storm systems in winter. The downward trend of the 10% probability line after mid-April is an indication of increasing atmospheric turbidity at this time of year.

[11]Solar radiation converted to a fraction of outer limits radiation is an index of transmittance.

Table 4.—Daily solar radiation probabilities by Climatological Week and outer limits radiation at midweek, 1968-77

[Calories per square centimeter per day]

Week	Period	Outer limits	Percent probability of receiving at least the indicated amount of solar radiation								
			90	80	70	60	50	40	30	20	10
1	Mar. 1-7	668	194	307	371	414	441	464	481	492	501
2	Mar. 8-14	705	185	324	396	436	460	481	496	508	522
3	Mar. 15-21	740	196	364	429	462	485	506	524	539	553
4	Mar. 22-28	774	263	391	453	489	515	532	546	560	575
5	Mar. 29-Apr. 4	807	303	414	473	512	536	557	573	588	606
6	Apr. 5-11	840	259	423	500	549	579	609	629	645	662
7	Apr. 12-18	871	261	453	510	549	582	618	638	650	664
8	Apr. 19-25	898	274	443	515	557	602	629	648	665	687
9	Apr. 26-May 2	923	351	471	535	581	618	646	665	680	706
10	May 3-9	947	308	450	545	599	634	663	682	701	724
11	May 10-16	966	348	471	563	617	647	671	691	707	726
12	May 17-23	983	352	474	550	609	649	669	690	707	725
13	May 24-30	995	428	498	547	598	647	673	697	717	736
14	May 31-June 6	1,002	431	499	546	596	641	671	691	715	741
15	June 7-13	1,009	439	522	579	623	656	676	696	720	744
16	June 14-20	1,012	501	582	627	658	680	702	719	738	750
17	June 21-27	1,013	486	582	626	658	679	697	714	733	749
18	June 28-July 4	1,011	455	550	607	641	667	687	708	733	748
19	July 5-11	1,005	432	526	588	626	656	680	694	711	725
20	July 12-18	994	417	521	577	614	636	660	679	696	717
21	July 19-25	979	408	503	571	607	630	649	666	683	702
22	July 26-Aug. 1	964	412	511	569	598	625	643	658	675	696
23	Aug. 2-8	947	426	507	553	592	620	634	652	663	680
24	Aug. 9-15	929	423	502	553	587	611	625	640	653	667
25	Aug. 16-22	905	371	471	523	553	575	597	613	626	642
26	Aug. 23-29	878	320	435	492	536	558	579	595	607	623
27	Aug. 30-Sept. 5	846	277	402	465	508	541	557	573	587	602
28	Sept. 6-12	813	232	358	431	484	515	534	549	564	577
29	Sept. 13-19	779	171	319	393	456	491	517	534	545	561
30	Sept. 20-26	745	171	320	380	436	475	494	509	522	536
31	Sept. 27-Oct. 3	708	207	366	421	455	476	491	503	510	524
32	Oct. 4-10	670	211	362	402	429	449	462	470	480	490
33	Oct. 11-17	632	145	297	360	398	417	432	442	453	461
34	Oct. 18-24	596	107	209	334	372	392	405	416	427	436
35	Oct. 25-31	561	97	206	316	348	369	380	390	399	409
36	Nov. 1-7	529	103	206	291	331	348	360	370	382	395
37	Nov. 8-14	498	120	227	284	312	328	339	349	356	368
38	Nov. 15-21	470	136	209	261	291	307	319	326	335	345
39	Nov. 22-28	447	143	201	253	277	295	304	313	321	328
40	Nov. 29-Dec. 5	429	135	200	255	274	284	293	300	308	315
41	Dec. 6-12	416	148	220	254	270	278	284	291	297	305
42	Dec. 13-19	409	160	222	249	263	271	278	283	290	300
43	Dec. 20-26	407	155	204	232	252	265	276	282	290	301

Table 4.—Daily solar radiation probabilities by Climatological Week and outer limits radiation at midweek, 1968-77 — *Continued*

[Calories per square centimeter per day]

Week	Period	Outer limits	Percent probability of receiving at least the indicated amount of solar radiation								
			90	80	70	60	50	40	30	20	10
44	Dec. 27-Jan. 2	412	131	182	222	249	268	280	289	300	310
45	Jan. 3-9	420	127	178	225	255	276	289	299	307	316
46	Jan 10-16	434	130	189	242	273	288	297	305	312	321
47	Jan. 17-23	453	143	216	263	288	301	310	317	324	335
48	Jan. 24-30	480	127	226	283	302	317	328	337	346	355
49	Jan. 31-Feb. 6	512	146	266	311	332	346	358	367	374	381
50	Feb. 7-13	546	120	246	309	348	373	389	397	404	410
51	Feb. 14-20	583	175	274	335	370	393	406	416	426	437
52	Feb. 21-28(29)	625	184	281	341	383	414	429	442	456	468

Seasonal variation in outer limits radiation, clear-day and all-days SR, all-days +NR, and soil and air temperature are shown in figure 13. The curve of outer limits radiation is symmetrical about the summer solstice line; the curve of clear-day SR is not. Because of varying atmospheric turbidity, SR is higher for a time before than it is after the summer solstice. Clear-day SR plotting points are averages of the three highest daily SR observations during each Climatological Week over the 10-year span (the average of the highest 3 of 70 observations). The maximum difference in average clear-day SR for dates equidistant from the summer solstice is 7%, between May 9 and August 5. Similar clear-day SR curves have been reported for other Great Plains locations (Baker and Klink 1975) and Twin Falls, Idaho (Fritz 1949).

Average all-days daily SR and average all-days +NR were calculated as the average of all daily observations for each month over the 10-year study period (approximately 3,000 observations). The maximum points of these curves are closer to the summer solstice line and the curves are more nearly symmetrical about the line than the clear-day SR curve, because at Amarillo the months following the summer solstice usually have less cloud cover and more hours of sunshine than months before the solstice (table 5).

The curve of average daily air temperature by months is the average of daily averages; the curve of average soil temperature by months is the average of 8-a.m. mid-month soil temperature at a depth of 6 inches. Because of energy storage in the soil, maximum air and soil temperature occur about a month later than maximum SR (see also McWhorter and Brooks 1965).

Clear-sky solar- and net-radiation flux recorded at Bushland at solar noon from 1972 to 1977 (770 observations) is shown in figure 14. This procedure (Brooks et al. 1963) makes more (and higher quality) data available for analysis than analyzing the total SR on clear days because skies are often completely clear at the moment of solar noon, but few days, especially in summer, are completely clear for the entire day. The SR curve was drawn by eye; the NR curve was drawn through monthly averages because the NR observations were so dispersed. Net radiation values were more dispersed because soil moisture and air humidity have a greater effect on NR than on SR. The dotted line (formed by "folding back" the SR curve at the summer solstice line) shows the effect of seasonal differences in atmospheric turbidity. When days equidistant from the summer solstice are compared, the maximum difference (between April

(*Continued on page 19.*)

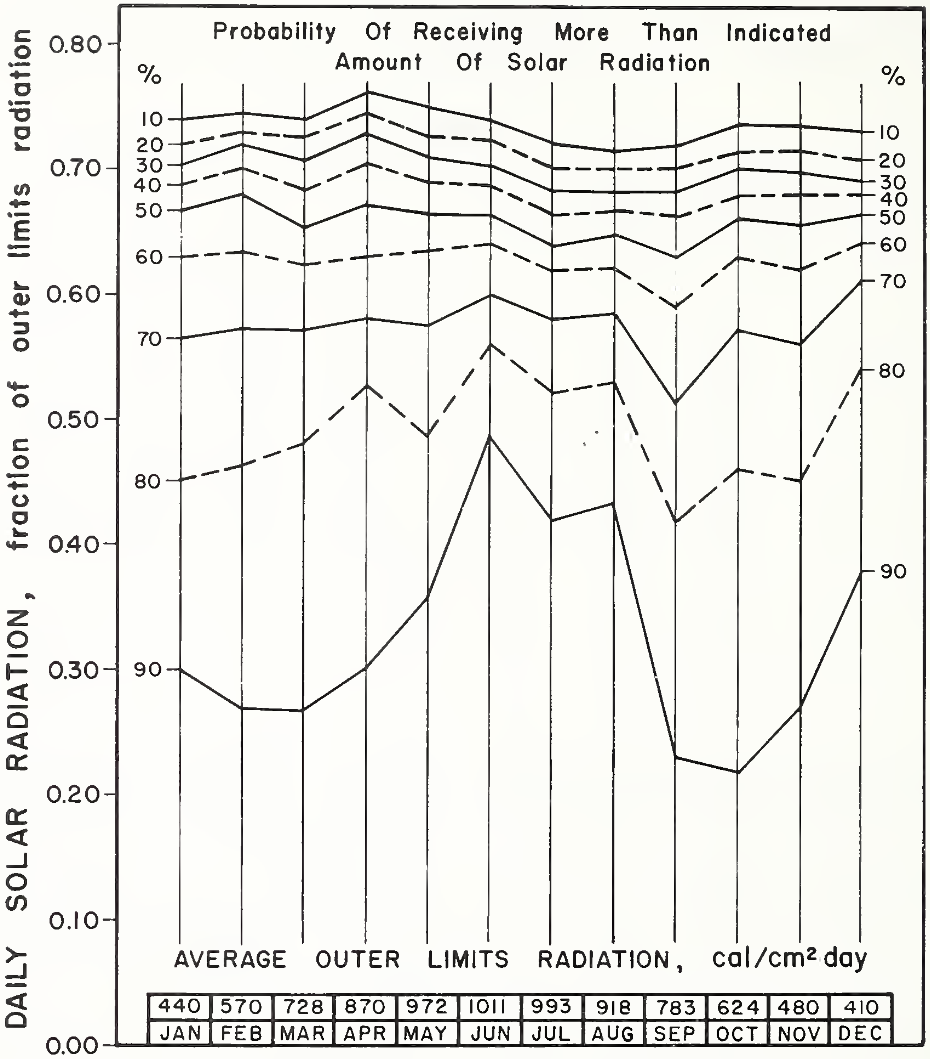

FIGURE 12.—Daily solar radiation probabilities (with solar radiation expressed as a fraction of outer limits radiation) at midmonth throughout the year at Bushland, Tex.

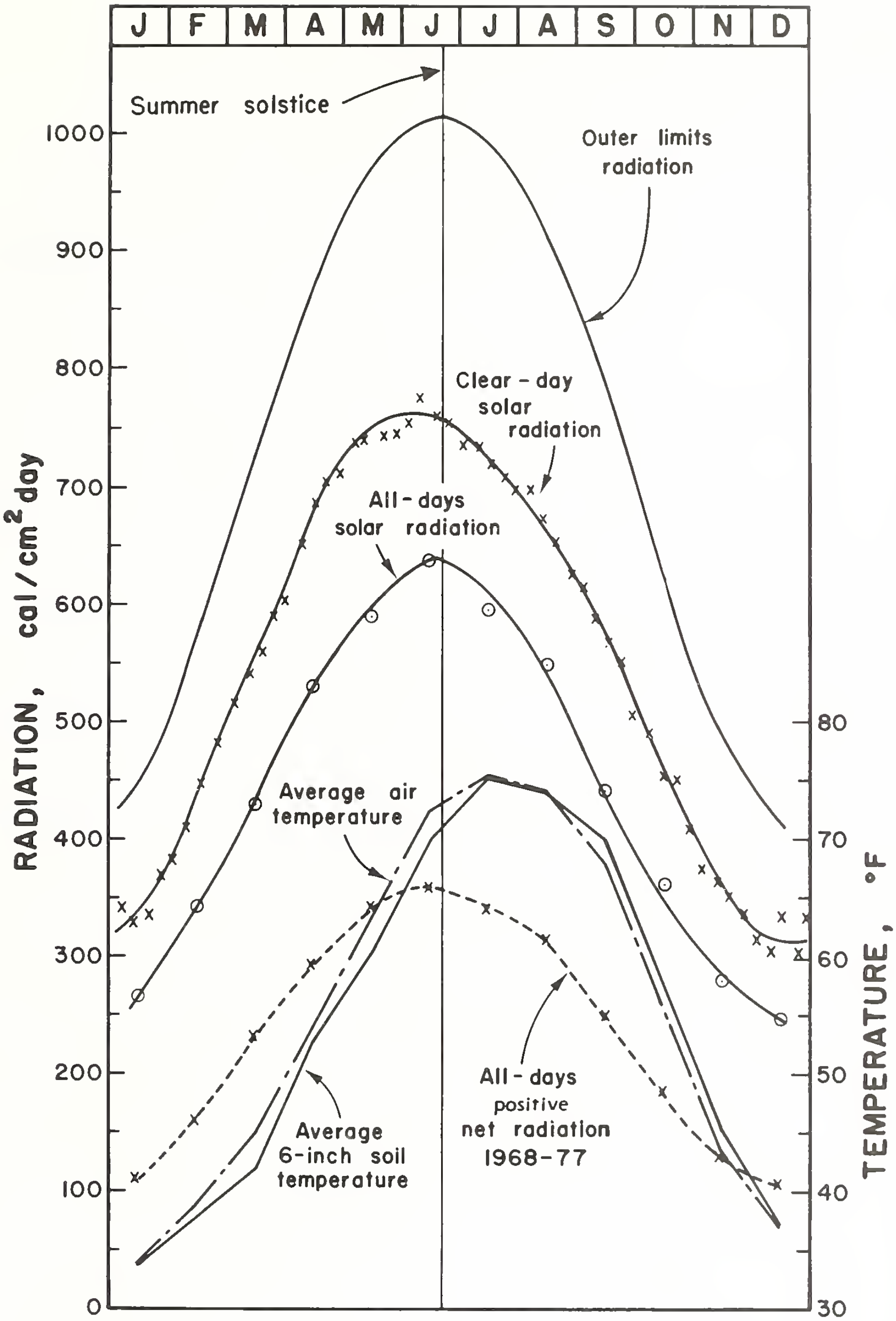

FIGURE 13.—Monthly averages, 1968-77: (A) outer limits radiation; (B) clear-day solar radiation; (C) all-days solar radiation; (D) all-days positive net radiation; (E) air temperature; and (F) 8-a.m., midmonth, 6-inch soil temperature.

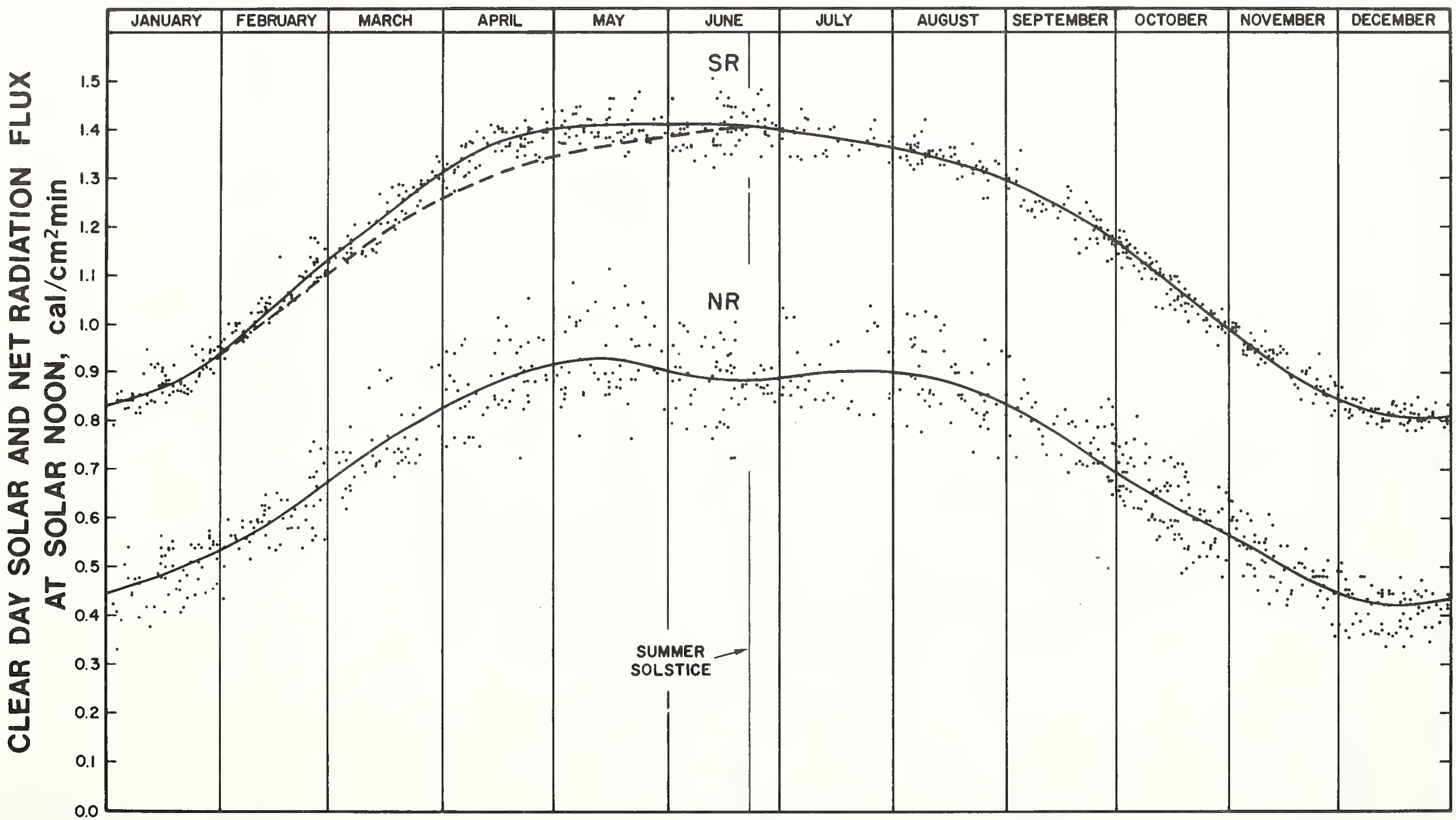

FIGURE 14.—Solar radiation (SR) flux and net radiation (NR) flux at solar noon under cloudless skies, Bushland, Tex., 1972–77. The dash line is the mirror image of the curve after the summer solstice.

Table 5.—Monthly and annual averages of precipitation, possible sunshine, sky cover, and number of clear, partly cloudy, and cloudy days near Bushland, Tex.[1]

Month	Average precipitation[2] (in)	Average possible sunshine (percent)	Average sky cover[3] (tenths)	Average No. of clear days	Average No. of partly cloudy days	Average No. of cloudy days
Jan. ...	0.41	69	5.0	13	7	11
Feb. ...	.46	69	5.1	11	7	10
Mar. ...	.67	72	5.2	12	8	11
Apr. ...	1.14	73	5.0	12	8	10
May ...	2.64	73	5.0	11	11	9
June ...	2.92	77	4.3	14	11	5
July ...	2.63	77	4.6	13	12	6
Aug. ...	2.74	78	4.2	15	10	7
Sept. ...	1.64	74	4.0	16	7	7
Oct. ...	1.65	74	3.8	17	7	7
Nov. ...	.71	73	4.3	15	7	8
Dec. ...	.53	68	4.7	14	7	10
Annual	18.15	73	4.6	163	102	100

[1]Precipitation was measured at Bushland but all other data were measured 20 mi. east of Bushland at the Amarillo, Tex., Air Terminal.

[2]39-yr average.

[3]Sunrise to sunset.

Source: U.S. National Oceanic and Atmospheric Administration (1973).

17 and August 27) is about 5%, somewhat less than the 7% difference obtained by using this procedure with the weekly-average clear-day SR curve of figure 1.

The reason the solar noon clear-day NR flux curve dips in mid-June is uncertain, but it may have been caused by a lowering of the air moisture content at a time when the area's two staple crops are not transpiring actively. Wheat is ripe at this time, and most of the grain sorghum is in the seedling stage.

Radiation and Evapotranspiration

By far the greatest use made of NR data so far has been for estimating water use by an irrigated crop (for which NR is the most important parameter). Evapotranspiration is sometimes estimated from whole-day NR (radiation balance), but better results are usually obtained if only daytime NR minus positive (daytime) soil heat flow (+SHF) is considered, since plant stomates usually close and transpiration nearly stops after sundown.

Commonly used methods of estimating evapotranspiration from NR are the combination method (Penman 1948) and the Bowen ratio method (Tanner 1960, Tanner and Lemon 1962, Fritschen 1965, Rose 1966, Fritschen 1967). The combination method estimates the combined effect of NR, aerodynamic mixing, and the air's vapor pressure deficit. The Bowen ratio method divides NR according to the two main ways it is used, to evaporate water and to heat the air. Since both methods require difficult measurements of air temperature and humidity gradients as well as NR (or its estimate), the procedures have had limited use except in research. Hopefully, however, with increased understanding of the evaporation process it will be possible to estimate evapotranspiration of a specific vegetated surface using NR measured over a standard vegetated surface (such as shortgrass or mowed grass) and ordinary weather observations, all made at a standardized agroclimatological station (Gardner et al. 1975). What is currently needed is to accumulate data relating NR to SR[12] and to determine the

[12]Solar radiation data have been measured for a longer time than NR data, and are easier to obtain.

relationship between NR measured over a standard vegetated surface and that measured over other vegetated surfaces, such as staple irrigated crops (Linacre 1963, Polovarapu 1970).

At Bushland, over shortgrass, +NR averaged 53% of SR for the entire 10-year study period. The percentage was greater in summer than in winter and greater with wet than with dry soil.

Figure 15 shows daily +NR plotted against daily SR, by months, for the entire 10-year period (3,653 data points). The straight line (the same for all graphs) was drawn by eye through the origin to best fit the data during the growing-season months (April through September). The mathematical expression for this relationship is +NR=0.575SR. This equation[13] overestimates +NR at Bushland from October through March because dry soil and vegetation combined with a low sun angle at this time of year cause high reflection of SR. Also, when snow is on the ground, heat flow into or out of the soil nearly stops and both +NR and -NR drop to low values. Most of the conspicuously low data points on the graphs for October through March are the result of snow.

Rain can also cause erroneously low indications of NR by wetting and cooling (by evaporation) the top of the radiometer flux plate more than the bottom. For this reason we customarily discarded the NR data recorded when rain was falling. Bushland's semiarid climate favors measuring +NR because there is not much interference from rain and the precipitation that does occur is mostly after dark (Rasmussen 1971).

Cool soil temperature from a high evaporation rate, low reflection of solar radiation from wet soil, an abundance of green vegetation, and high atmospheric humidity can cause an unusually high ratio of +NR to SR. On 2 days (May 9, 1969 and March 31, 1973) the ratio of +NR to SR was especially high, 71% (fig. 15). Both days were clear and the soil was wet from recent heavy precipitation. May 9 followed a storm with 2.49 inches of rain; March 31 followed a storm that had 1.86 inches of rain and was also a day with very high wind speeds that increased the evaporation rate of soil water and cooled the soil.

[13]This relationship is very close to the regression equation Polovarapu (1970) obtained for +NR (on all days) versus SR from May through October at Guelph, Ontario.

The amount of +NR is related to the amount of ground cover; it is greater over heavily than over sparsely covered ground. For example, +NR measured over an irrigated sorghum field from June 30 to October 17, 1973, averaged 66% of SR, but measured over shortgrass sod, it was only 55% of SR. Similarly, +NR measured over irrigated wheat from March 28 to April 8, 1972, averaged 63% of SR; measured over shortgrass sod, it was only 57% of SR.

The energy of the latent heat of evapotranspiration (LE) of an irrigated crop (or by a nonirrigated crop in a humid climate) is usually about equal to that of the radiation balance (Tanner 1960, Tanner and Lemon 1962, Fritschen 1965, 1967). But on exceptionally hot, windy days because of advected energy, LE may be greater than the radiation balance by factors of as much as 1.3 in Wisconsin and 1.8 in Arizona (Fritschen 1965). In 1961 we found the accumulation of radiation balance energy over irrigated grain sorghum from July 13 to October 17 to be approximately the same as the accumulated LE for the whole period. But for a month, starting in mid-August, LE was about 16% greater than the radiation balance.

On a whole-day basis, net soil heat flow (SHF) is a very small fraction of the total energy budget; from the warmest day in summer to the coldest day in winter the range in soil heat content of 4 feet of soil is about the same as the energy of 2 days' LE of an irrigated crop (Russell 1952).

If only +NR values are being correlated with LE, it is customary to adjust them by subtracting positive (daytime) soil heat flow. In 1973 we compared the accumulated LE of an irrigated grain sorghum crop with the accumulated +NR minus +SHF. For the period June 30 to October 18, accumulated LE was about 0.8 times the accumulated energy of +NR minus +SHF, but during the period of the plants' peak water use the two were approximately equal.

Thus the two most common methods of estimating evapotranspiration from NR, involve subtracting either -NR or +SHF from +NR. In the sorghum field in 1961, -NR was 13% of +NR in July, 16% in August, and 25% in September (showing the effect of increasing nighttime hours). Daytime soil heat flow in an irrigated crop is a smaller but less variable fraction of +NR than is -NR, in the range of 8 to 10%. LE should thus be a slightly larger fraction of the radiation balance than of +NR minus +SHF.

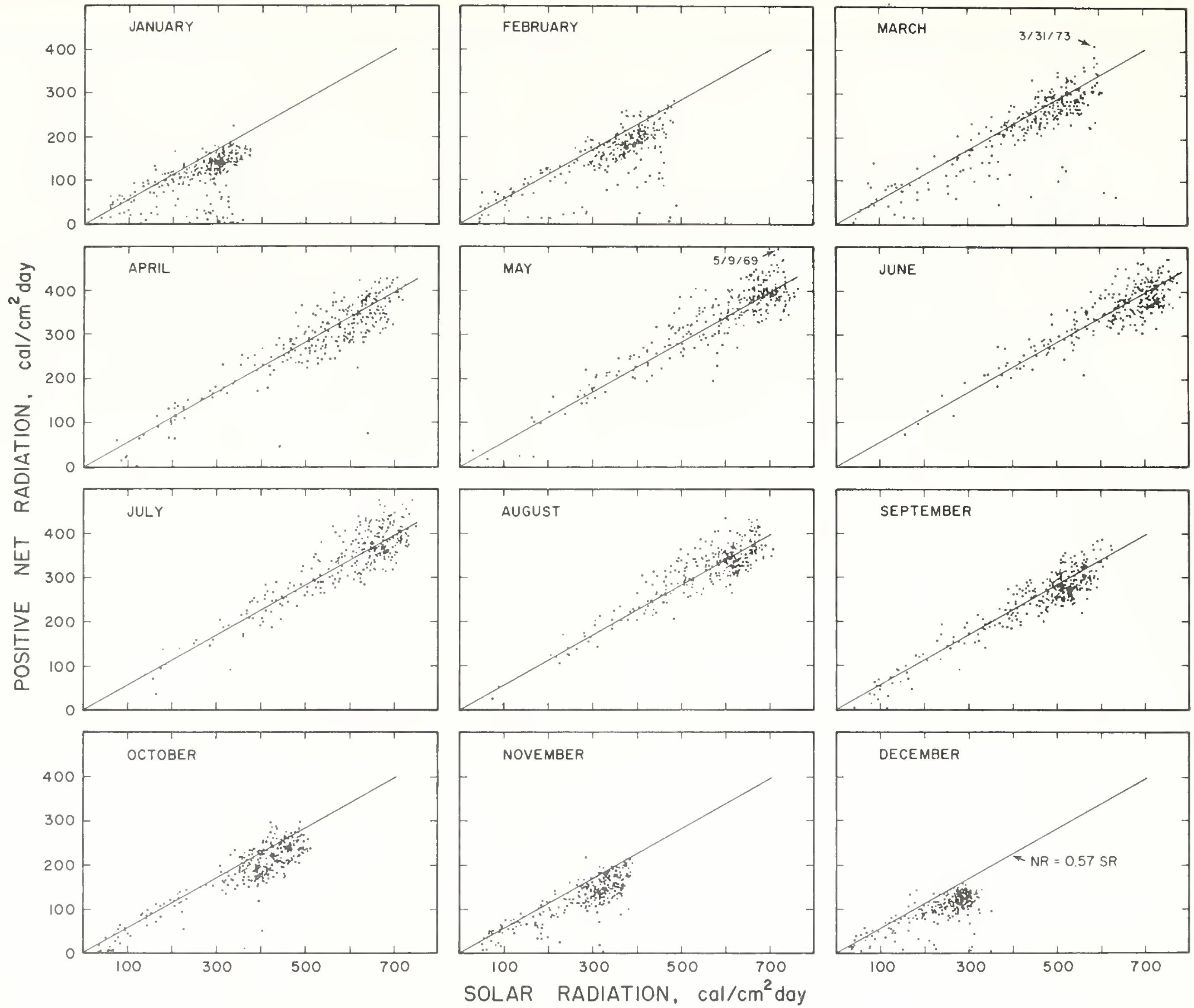

FIGURE 15.—Daily positive net radiation (over shortgrass sod) versus daily solar radiation, 1968-77, by months.

Some other methods estimate evapotranspiration rate by multiplying SR flux by an empirical factor that varies with crop, growth stage, and location (Carreker 1963, Jensen and Haise 1963).

Interrelationships of Net Radiation Flux, Solar Radiation Flux, and Soil Heat Flow

The interrelationships among SR flux, NR flux and SHF can be shown by combining recorder traces. We have done this for four different situations (figs. 16 and 17).

Clear day with snow-covered ground.—On December 1, 1971, 10 inches of snow fell. On December 6, 3 inches of snow cover remained. With snow still on the ground, the soil heat flow remained at a very low negative level throughout the day (fig. 16A). Although the SR for the day was high (319 cal/cm²) the net SHF was only -9 cal/cm² (the negative sign indicates a net soil heat flow out of the soil). Most of the solar radiant energy was being returned to outer space by reflection from the white snow surface and as terrestrial (invisible, longwave) radiation (for which snow has a high emissivity).

Maximum negative fluxes of NR on December 6 occurred a short time after sunrise in the morning and a short time before sunset in the evening. This phenomenon was apparently caused by the high rate at which SR was reflected by the snow surface when the sun was at a low angle; it was not observed 4 days later after the snow had melted (fig. 16B). Total -NR was 104 cal/cm² and total +NR was only 15 cal/cm², resulting in a radiation balance of -89 cal/cm². Figure 16A illustrates how cold polar air masses are produced in winter as a result of a negative radiation balance; in snow-covered areas in northern latitudes, outgoing radiant energy exceeds incoming and the difference is taken from the air that is in contact with the ground.

Clear winter day with wet soil.—By December 10, 1971, the snow had melted, leaving the surface soil very wet, and frozen in the morning (fig. 16B). Wet soil should cause the ratio of +NR to SR to be above average. This did occur; +NR was 53% of SR, above the normal of about 43% for clear days at this time of year (fig. 15, tables 2, 3). Radiation balance for the day was +49 cal/cm². Although SHF underwent a large diurnal change, +SHF did not begin until just before noon because the soil was wet and frozen in the early morning. Net SHF for the day was -3 cal/cm²; energy from the radiation balance warmed the air or evaporated water, but did not warm the soil.

Clear day near the summer solstice.—On June 25, 1971, conditions favored a rapid increase in soil temperature. Net SHF for the day was +78 cal/cm². Solar radiation flux was near its maximum for the year, briefly reaching a rate of 1.48 cal/cm² min (1.04 hp/yd²) at solar noon and totaling 748 cal/cm² for the day (fig. 17A). Positive net radiation totaled 399 cal/cm² (53% of SR) and the radiation balance was +322 cal/cm² for the day. Positive soil heat flow was 29% of +NR.

Heat flow into the soil was exceptionally great because the sparse shortgrass vegetation did not shade the soil surface much and allowed the afternoon soil surface temperature to reach about 125° F. Had there been more vegetation, as in an irrigated field, +SHF would not have been as great. The daily +SHF in an irrigated wheat field in April 1972 averaged 10% of the daily +NR; in an irrigated grain sorghum field in August 1973, it averaged 8% of daily +NR.

Summer day, sunny in the morning and evening, with a shower at midday.—The recorder traces for August 3, 1971, show the effect of a small midday shower on NR and SHF. The shower occurred between 12:30 and 1:30 p.m. and totaled 0.08 inches (fig. 17B). The traces are correct where they show the reversal of the direction of SHF when the surface soil was cooled by the shower, but the decrease in +NR shown is probably exaggerated because evaporation causes the top and bottom of the flux plate to cool unequally. Once the rain stopped, however, the ventiliating blower quickly dried the flux plate and returned the net radiometer to normal operation. The shower cooled the soil surface and reduced the flux of outgoing longwave radiation for several hours. As a result, +NR was unusually high compared to SR, and heat flow into the soil nearly stopped. The shower caused a disproportionately larger reduction in +SHF than in +NR. Despite a radiation balance of +210 cal/cm², the net SHF for August 3 was -3 cal/cm². This showed that the radiation balance was used entirely for warming the air and evaporating water and not at all for warming the soil.

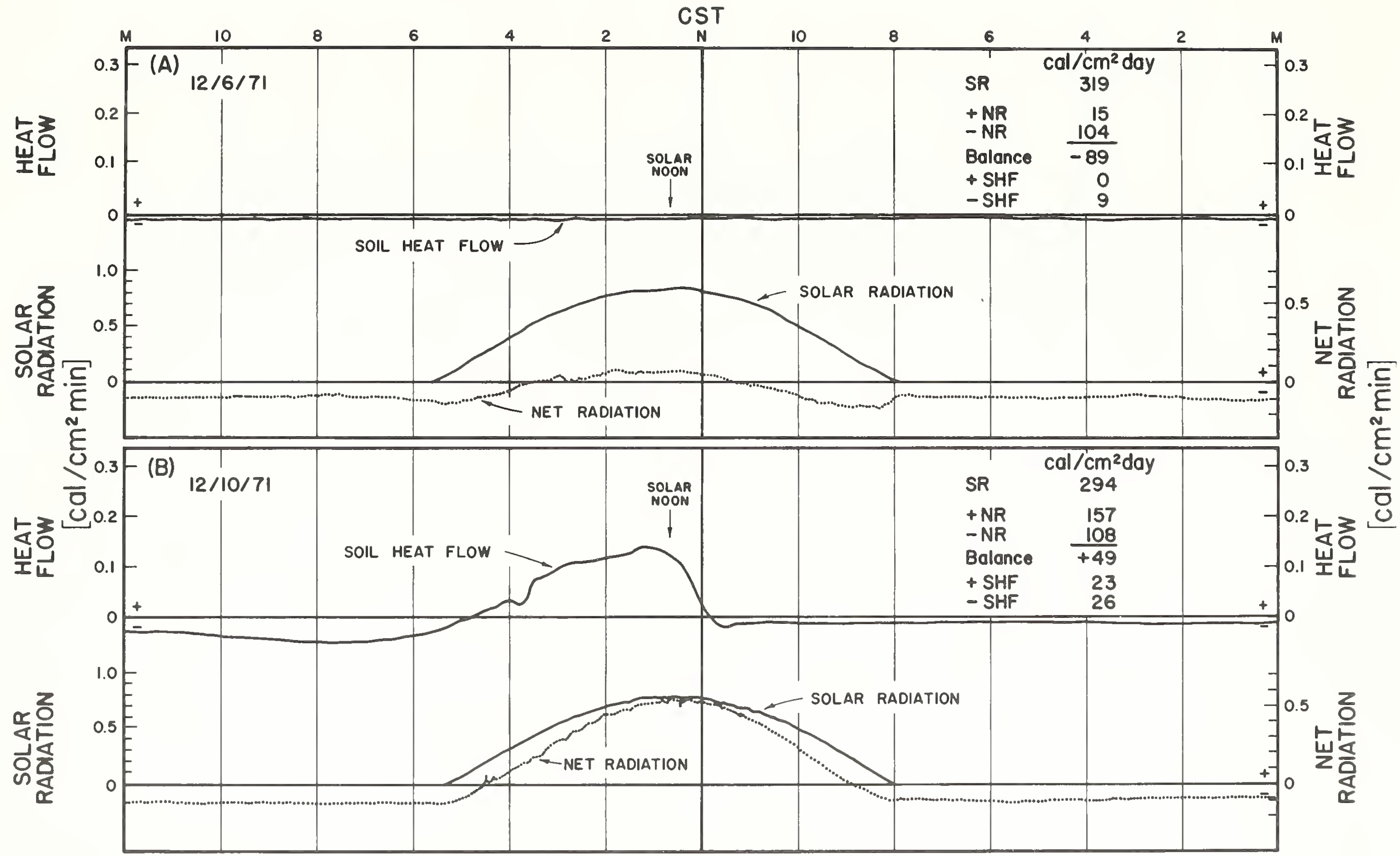

FIGURE 16.—Recorder traces of soil heat flow (SHF), net radiation (NR), and solar radiation (SR): (A) December 6, 1971, a clear day with 3 inches of snow on the ground; and (B) December 10, 1971, a clear day with soil wet from melted snow.

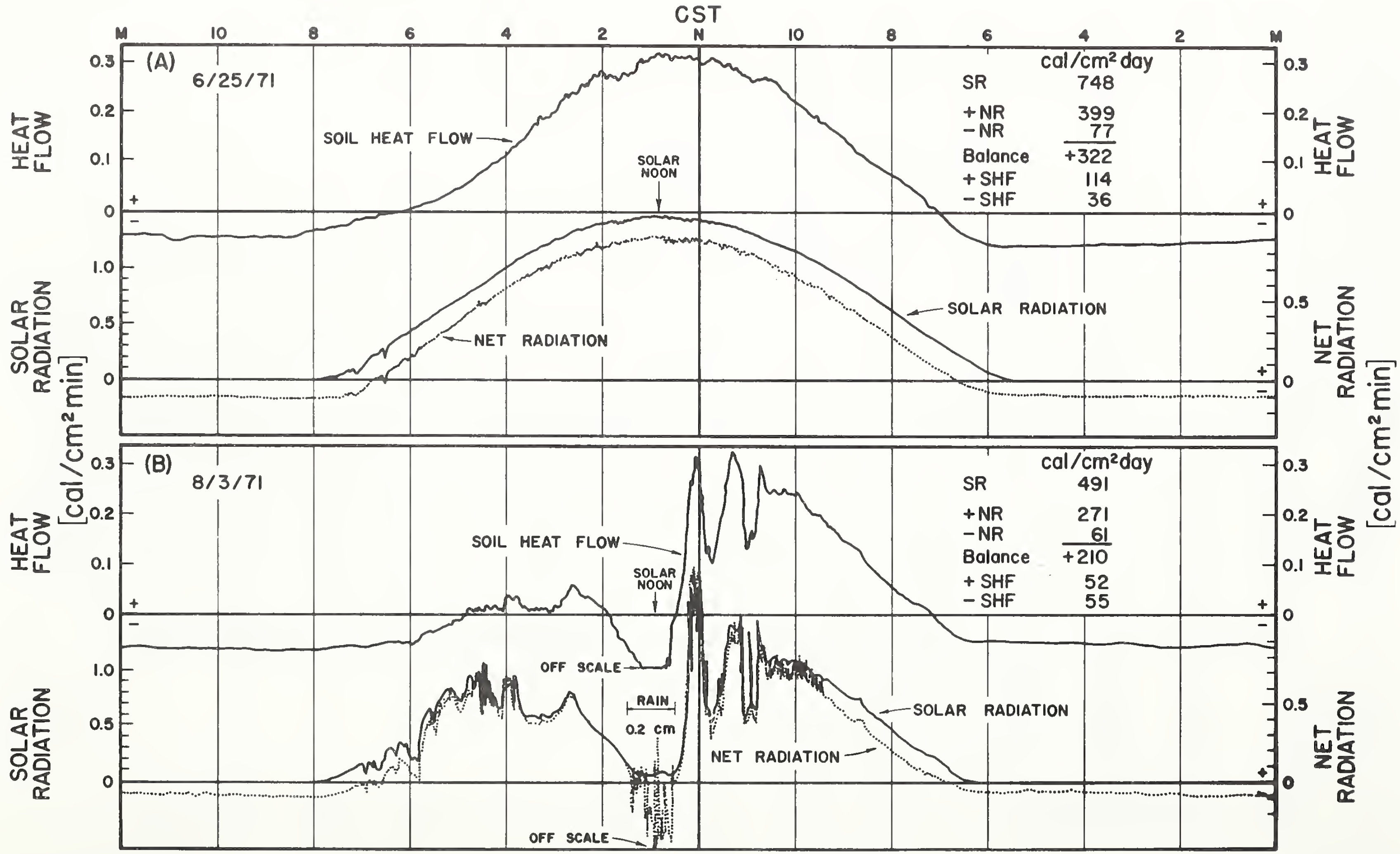

FIGURE 17.—Recorder traces of soil heat flow (SHF), net radiation (NR), and solar radiation (SR): (A) June 25, 1971, a clear day near the summer solstice; and (B) August 3, 1971, an otherwise clear day with cloudiness and 0.08 inch of rain between 12:30 and 1:30 p.m.

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